

Group Report: Earth System Dynamics in the Anthropocene

W. STEFFEN, Rapporteur

M. O. ANDREAE, B. BOLIN, P. M. COX, P. J. CRUTZEN,
U. CUBASCH, H. HELD, N. NAKICENOVIC,
L. TALAUE-MCMANUS, and B. L. TURNER II

THE EARTH SYSTEM IN THE ANTHROPOCENE

Human-driven changes to many features of the Earth system have become so ubiquitous and significant in magnitude that a new era for the planet — the “Anthropocene” — has been proposed (Crutzen and Stoermer 2001; Clark et al., this volume). Many of these changes are large in magnitude at the planetary scale, sometimes even exceeding natural flows in major aspects of biogeochemical cycling. In addition, anthropogenic changes invariably occur at rates that are much larger than those of natural variability, often by an order of magnitude or more. The magnitudes and rates of these changes, coupled with the fact that changes to a large number of Earth system processes and compartments are occurring simultaneously, has led to the recognition that the Earth is now operating in a “no-analogue state” (Steffen et al. 2004).

The features of this no-analogue state present challenges to human responsiveness, challenges that have not been experienced in coping with any previous environmental changes, which have occurred at local and regional scales. These features include the facts that:

- Large parts of the problem are global in scale, transcending any region, continent, or ocean basin on its own.
- Connectivity between different biophysical processes and geographical areas of the planet is much greater than previously thought, and the connectivity of human activities is increasing at a rapid rate.
- Human-driven changes to Earth system functioning operate on very long timescales, where the consequences of some human actions may be present for decades and centuries, and across very large space scales, where causes are spatially de-linked from consequences.
- The impacts of global change on human–environment systems can no longer be understood by simple cause-effect relationships, but rather in terms of cascading effects that result from multiple, interacting stresses.

- New forcing functions arising from human actions (e.g., synthetic chemicals) and rapid rates of change imply that the natural resilience of ecological systems may not be sufficient to cope with the change.

These features of the Anthropocene are already leading to discernible changes in the functioning of the Earth system and may well lead to accelerating change in many ways throughout this century (IPCC 2001; Steffen et al. 2004). Significant improvements in the ability to observe, understand, and simulate past, contemporary, and potential future change are essential to provide the knowledge base required to achieve global sustainability.

The aim of this report is to examine a few critical areas where human activities are having, or have the potential to have, significant impacts on the functioning of the Earth system. We begin by focusing more closely on the climate component of the Earth system before moving to broader considerations of geography and to a discussion of the potential for abrupt changes in several components of the Earth system. A brief discussion of the challenges for modeling and observation follows. We conclude by examining whether or not technical substitution or fix can address the issues raised earlier in the report.

CLIMATE SENSITIVITY

How does the increasing understanding of the role of aerosols change our understanding of the climate sensitivity to greenhouse gases?

Climate has been changing during the last century. The IPCC (2001) has established that the global mean temperature has increased by $0.6 \pm 0.2^\circ\text{C}$. About half of this increase has occurred during the last 40 years or so. It is also clear that this change is unique as compared with the rest of the last millennium (Mann et al. 1999), although there are some uncertainties about the variations of the mean temperature during this period as deduced from the many different indicators that have been used.

The IPCC has also concluded that the change during the twentieth century cannot be explained without including the role of increasing concentrations of greenhouse gases in the atmosphere during this period of time. Although few in the scientific community now contest this conclusion, there are still occasional claims that the recent warming is the result of internal natural variations of the climate system. To accept this as a plausible possibility, the following question must be answered: Why did a major change of the internal variability occur toward the end of the twentieth century? Further, such changes must also be associated with changes of the internal fluxes of energy through the atmosphere. A plausible analysis to support the idea that random internal variations would be the prime reason for the increase of the global mean temperature during the twentieth century has yet to be presented. The conclusion that human activities have led to a significant change of climate, characterized to first order by a global warming, is now beyond reasonable doubt.

The observed increase in the global mean surface temperature is the net result of opposing forcings and effects. Greenhouse gases exert a warming forcing that is modified by feedbacks, most prominently as a result of changes in atmospheric water vapor and clouds. Aerosols have direct, radiative cooling and warming effects as well as a series of indirect effects due to aerosol-induced changes in cloud properties, abundance, and dynamics. Large uncertainty is associated both with the magnitude of the enhancement of greenhouse gas forcing (warming), resulting from cloud feedbacks, and the (net cooling) aerosol effects, including the various aerosol–cloud effects. Consequently, the observed temperature increase could be explained by a large greenhouse gas effect (implying a large greenhouse gas–cloud feedback), which is opposed by a large aerosol–cloud effect, or alternatively by small greenhouse gas–cloud and aerosol–cloud effects. At present, these alternatives yield nearly the same solution for the interpretation of the observed climate history. The magnitude of the greenhouse gas–temperature–cloud feedback is a long-standing uncertainty. The magnitude of the cooling owing to aerosol-related effects is also difficult to determine directly because of the inhomogeneous distribution of aerosols, as well as clouds, and limited knowledge about their optical characteristics.

There is, however, a very important difference in the way these alternatives affect future climate change. “Climate sensitivity” is defined as the amount of climate change per amount of radiative forcing (greenhouse gas, aerosol) added to the atmosphere (usually expressed as degrees of global temperature rise per doubling of CO_2 in an equilibrium climate model run). At present, different climate models predict very different climate sensitivities, mostly because they contain different ways of representing greenhouse gas–cloud feedbacks, and there appears to be no *a priori* way of deciding which of these models gives the “better,” more accurate answer regarding climate sensitivity. The net effect of the present-day greenhouse gas and aerosol forcings (including delayed effects due to latency in the system) is simply the observed present-day climate change. Therefore, the potentially large aerosol effects (as summarized by Anderson et al. 2003) would imply that climate sensitivities are more consistent with the high end of the range presented in IPCC (2001).

A quantitative analysis, based on Crutzen and Ramanathan (this volume), of the current situation illustrates the qualitative point made above. The enhanced concentrations of greenhouse gases in the atmosphere have reduced the outgoing long-wave radiation by $2.7 \pm 0.5 \text{ W m}^{-2}$ (IPCC 2001). This energy flux must be balanced by (a) increases in outgoing radiation due to warming at the Earth’s surface, (b) flux of heat into the Earth’s surface, primarily the surface ocean, and (c) the sum of aerosol radiative effects and albedo feedbacks among aerosols, greenhouse gases, and clouds. We can deduce the approximate outgoing flux of energy from the observed warming at the surface of the Earth (Ramanathan 1981) to be $1.5 \pm 0.5 \text{ W m}^{-2}$. The smaller value of the range (1.0 W m^{-2}) includes the role of feedback mechanisms, primarily due to water vapor, which reduce

the long-wave radiation to space (water vapor feedback), whereas the large value (2.0 W m^{-2}) is obtained for an atmosphere without a water vapor feedback. The increase of the temperature in the atmosphere is also driving a flux of heat into the oceans of about $0.32 \pm 0.15 \text{ W m}^{-2}$ (Levitus et al. 2000; Barnett et al. 2001). To achieve a balance of the energy budget, aerosol–greenhouse gas–cloud interaction processes must induce a net flux of radiation back to space, ranging from about 0 W m^{-2} in the case of no water vapor feedbacks, which is known to be unrealistic (IPCC 2001), to $1.9 \pm 0.5 \text{ W m}^{-2}$, corresponding to 60% of the greenhouse gas forcing, if the feedback mechanisms due to water vapor, etc. are considered. In effect, the cooling that results from aerosol-related processes counteracts a significant increase of surface temperature that would have otherwise occurred in their absence. It is important to note that this quantitative analysis is valid for the situation around the year 2000 and does not scale into the future as both greenhouse gases and aerosol loadings in the atmosphere will change with time.

This result has a major consequence for estimates of future climate change. Atmospheric aerosol loadings will not likely increase strongly; they may even decline in the coming decades. Thus, their cooling effect will level off or decrease. On the other hand, greenhouse gases will continue to accumulate in the atmosphere. In the case of high climate sensitivity, this must lead to a considerably sharper increase in global temperatures than has been experienced so far and to temperature increases closer to the upper end of the range given by the IPCC Third Assessment Report (2001), even without extreme emission scenarios.

It is evident that great effort should be invested in resolving these issues. To make progress in this direction, we need (a) to improve the representation of cloud effects in general circulation models (GCMs), (b) to develop parameterizations of aerosol effects on clouds and find ways to incorporate them into GCMs, and (c) to use the analysis of parameters besides temperature (precipitation, heat fluxes, etc.) and of the spatiotemporal distribution of climate change to diagnose the relative contributions of greenhouse gas and cloud effects. In addition, a much more systematic, consistent, and continuous climate observing system is required to test models and to improve understanding of the climate system in general.

EARTH SYSTEM GEOGRAPHY IN THE ANTHROPOCENE

**What are the important regions in the Earth system and in what ways?
Do midlatitudes really matter compared to the tropics and high latitudes?
Can we differentiate geographically between drivers and impacts of
global changes?**

The Earth's surface is highly heterogeneous, and the distribution of humans and our activities are highly skewed, features that have important implications for

the functioning of the Earth system in the Anthropocene. The implications of heterogeneity vary, however, according to the question being asked. For example, very different subglobal patterns of important areas, or *hot spots*, emerge from analyses of the physical climate system and of the socioeconomic sphere of the Earth system, respectively. For any aspect, however, understanding of the Earth system is only as good as its least understood region, implying that the scientific effort must be much better distributed around the globe than in the past.

In terms of *socioeconomic aspects*, an important feature is that the areas that are currently important as drivers of change (the midlatitudes) are not necessarily those that will largely bear the brunt of global change impacts (e.g., Shah 2002) and that maintain critical processes for Earth system functioning (the tropics, e.g., the role of tropical forests in heat and water vapor exchange). Yet understanding, either in a biophysical or a socioeconomic sense, is far less for the tropics than for the midlatitudes, and the disparity in research effort appears to be increasing. The implications of this for the quest for global sustainability are significant, as projections of demographic change suggest that by 2030 about 90% of the population will live in the tropics (UN 2001). The increasing connectivity of the global economy (e.g., through production-consumption chains of key commodities like food) are linking the tropics more tightly to the midlatitudes so that impacts in the tropics will reverberate further in the Earth system.

The impacts of human-driven change in the tropics for the functioning of the Earth system are equally less understood in comparison to the midlatitudes. Much contemporary land-cover change is occurring at local and regional scales in the tropics, usually involving conversion of forest to agriculture and pasture as well as secondary regrowth that is subsequently recut. Nearly all of the rapid change to the structure of the coastal zone ecosystems is also occurring in the tropics. Understanding of the implications of these changes for biogeochemical cycling, biodiversity, and the physical climate system considerably lags behind that for similar changes in the midlatitudes. One exception is the Large-scale Biosphere-Atmosphere Experiment in Amazonia (Nobre et al. 2002), where a decade-long, multinational study involving hundreds of researchers is rapidly building a better understanding of the dynamics and consequences of land-cover change in the Amazon Basin, from the local up to the global scale. Many other examples could be given, all pointing to the need for a significantly enhanced research effort in the tropics in all aspects of global change.

For the *physical climate system*, a few well-known hot spots have received considerable attention by the research community. Examples include El Niño research in the tropical Pacific Ocean and a rapidly increasing number of investigations of the potentially critical branch of the thermohaline circulation (THC) in the North Atlantic Ocean. The Southern Ocean, however, has been much less studied. Issues such as deepwater formation and its role in THC and the relative importance of the Southern Ocean in the marine carbon cycle demand increased attention.

A strong case can also be made for an enhanced effort in the high latitudes, which are now experiencing the most rapid rates of climate change and which also play an important role in the Earth system through the albedo–ice feedback, the taiga–tundra feedback, and the potentially large releases of carbon compounds from the terrestrial biosphere with increased warming. All of these potential feedbacks (e.g., possible disappearance of Arctic sea ice in summer, movement of boreal forests northward) are positive, that is, they enhance the warming that triggered them and could occur within a 50- to 100-year time frame. This suggests that a concerted effort is required to improve the knowledge base of high-latitude systems under rapid warming; the need is particularly acute for northern Eurasia, which is clearly a very important region from the perspective of Earth system dynamics and which currently suffers from decaying scientific infrastructure and a lack of adequate support for the large scientific community that has worked there through much of the previous century.

On a longer time frame (a few millennia), an intriguing question concerns the sensitivity of the area north of 65° , particularly in North America, as it is known to be the site of glacial inception and thus might be the starting point of the next ice age. Although solar output is currently increasing slightly, and thus is a minor contributor to the observed warming, solar insolation will reach a minimum during the next 200 to 500 years as a result of orbital variation. Model experiments suggest that in a 280 ppm CO_2 world, such insolation conditions could lead to a formation of an ice sheet, although this would almost surely require significant additional cooling due to, for example, injection of massive amounts of aerosols into the atmosphere from volcanoes or anthropogenic activities. However, given that the minimum in solar insolation is rather shallow and will not be much different from current insolation (e.g., compared to greenhouse gas forcing), it appears that the projected increased level of CO_2 over the next 200 to 300 years will more than compensate for the insolation minimum. In addition, another study (Loutre and Berger 2000) suggests that changes in orbital forcing alone, without any anthropogenic increase in greenhouse gas concentration in the atmosphere, will lead to a continuation of the present interglacial period for another 30,000 to 50,000 years. Suggestions of glacial inception notwithstanding, it must be clearly stated that the most important issue by far in the high latitudes, in terms of immediacy and rate and magnitude of change, is the current strong warming and the potential for positive feedbacks to the climate system.

“ACHILLES’ HEELS” IN THE EARTH SYSTEM

What are the Achilles’ heels in the Earth system? Can abrupt changes in the operation of the Earth system be anticipated and predicted? Can those that are most susceptible to triggering by human actions be identified?

Earth’s environment shows significant variability on virtually all time and space scales, and thus global change will never be linear or steady under any scenario.

Of particular interest and importance are abrupt changes that can affect large regions of Earth. For example, the paleo-record gives unequivocal evidence of such abrupt climate change in the recent past, such as the Dansgaard/Oeschger (D/O) events that happened in the period 70,000 to 15,000 years ago (Grootes et al. 1993). Although presumably not having been of global scale, the significance of abrupt changes such as D/O events is that (a) they can involve a scale of change, up to 10°C in a decade or so (see Rahmstorf and Sirocko, this volume), which could devastate modern economies should such changes occur in these regions, (b) they have occurred during the time of human occupation of the planet, and (c) they have occurred in regions (western Europe and North America) now heavily populated. Abrupt changes cannot be dismissed as either implausible or irrelevant in terms of spatial or temporal scales.

Furthermore, one abrupt change of a different kind has already occurred. The formation of the ozone hole over Antarctica was the unexpected result of the release of human-made chemicals thought to be environmentally harmless (see Crutzen and Ramanathan, this volume; Schneider et al. 1998). The event was one of chemical instability in the atmosphere rather than an abrupt change in the physical climate system. In addition, it occurred in a far distant part of the planet, well away from origin of the cause. In several ways, humankind was lucky in that the ozone hole could have been global and present through all seasons (Crutzen 1995).

Such evidence of instabilities in the chemical system in the stratosphere and in the THC in the North Atlantic (thought to underlie the D/O and Heinrich events seen in the Greenland ice core records; Ganopolski and Rahmstorf 2001; Clark et al. 2001) gives a warning that human activities could trigger similar or even as-yet unimagined instabilities in the Earth system, in its physical, chemical, or biological components or in coupled human–environment systems.

Abrupt Changes in the Physical Earth System

Initially it may appear an impossible task to anticipate abrupt changes in the Earth system (NRC 2002; cf. Schneider et al. 1998). Abrupt changes, by definition, occupy small regions of a potentially high-dimensional climate phase space, such that it is impractical to search for such changes with a comprehensive model (such as a GCM). However, the special nature of abrupt changes actually makes them amenable to analytical techniques. By “abrupt” we mean changes that occur much more quickly than changes in anthropogenic forcing. In a typical setting, for this to occur requires the existence of multiple equilibria (or “fixed points”), of which the “current” Earth system equilibrium state becomes linearly unstable or even vanishes (such a point in the phase space/forcing diagram is called “bifurcation”). Under these conditions an arbitrarily small perturbation to the formerly stable equilibrium can result in a transition to a different equilibrium state even in the absence of changes in forcing.

The classical example is the ocean's THC, which in its current state transports heat from equator to pole, helping to keep western Europe unusually warm for its latitude. Thermohaline circulation takes warm surface waters to the North Atlantic, where they cool (releasing their heat to the atmosphere), become denser, and sink to depth. Simple models of the THC exhibit both "on" and "off" states with the potential for rapid switching between these states based on the freshwater input to the North Atlantic. The current "on" state can be destabilized by additional freshwater inputs to the North Atlantic, which freshen the surface waters, make them less dense, and inhibit sinking (Rahmstorf 2000). It is hypothesized that such a perturbation arose from the melting of the North American ice sheet, leading to a shutdown of the THC and a cooling of the Northern Hemisphere during the Younger Dryas event 12,000 years ago. Some comprehensive GCMs also suggest that the THC could be similarly shut down by increases in rainfall at high latitudes under greenhouse warming (thereby increasing the freshwater flow in Russian rivers to the Arctic Sea); however, this sensitivity is by no means common to all models.

Thermohaline circulation offers an excellent example of where a possible abrupt change in the Earth system has been anticipated using a combination of models and data. Although the precise timing of a THC shutdown cannot be predicted with any certainty, the topology of the THC phase space is sufficiently well known to inform attempts to monitor for signs of an impending switch to the off state. Furthermore, the transition from one equilibrium state to another (triggered by a bifurcation) is typically preceded by enhanced variability in the THC (Kleinen et al. 2003), offering an additional warning of possible change.

Other aspects of Earth system dynamics are also believed to exhibit multiple equilibrium states and may therefore display abrupt transitions between these equilibria. These include evidence for a transition from a green to an arid Sahara in the mid-Holocene 5,500 years ago (Claussen et al. 1999; deMenocal et al. 2000) and model-derived results which suggest that Greenland can support both ice-covered and ice-free conditions under current CO_2 conditions. These sub-systems display "hysteresis" or path-dependence in their response to control variables. Thus, for example, under sustained increases in CO_2 level (equivalent to a 3°C warming over millennia), the Greenland ice sheet is predicted to melt in an irreversible manner (IPCC 2001), such that much lower CO_2 values would be required before it would return.

The generic properties of multiple equilibria, linear instabilities, and bifurcations offer the possibility of cataloguing possible abrupt changes in the Earth system in a much more thorough way than has been achieved to date. In principle, Earth system equilibria can be defined by setting time derivatives to zero within current Earth system models. Linear stability theory requires that only linear terms are kept within the full nonlinear equations, significantly simplifying the analysis. Therefore, the initial cataloguing of possible Earth system instabilities can be based on well-founded analytical and semi-analytical

mathematical techniques, potentially providing a map of hot spots in the Earth system where abrupt change is possible. Once an equilibrium has been found in a model, path-continuation numerics (Feudel and Jansen 1992) make it possible to derive automatically a bifurcation diagram. This technique is becoming increasingly feasible even for comprehensive models (Dijkstra 2000).

Another approach is to use the phenomenon of stochastically induced jumps between multiple equilibria. According to Kramer's rule (Gardiner 1994), an increase in noise in a complex system can trigger an abrupt shift from one state to another. The related timescale is determined by the potential well between the equilibrium states and the amplitude of the noise. The interplay between multiple equilibria and noise can amplify an existing periodic forcing ("stochastic resonance"; Gammaitoni et al. 1998) or may trigger an excitable cycle ("coherence resonance"; Pikovsky and Kurths 1997). Stochastic resonance occurs where the period of the forcing matches the time for transitions between alternative equilibrium states of the system. In analogy, coherence resonance occurs where the time for excitation by noise fulfills a certain matching condition with the period of the excited cycle. Stochastic resonance has been suggested as a contributing factor in D/O events (Ganopolski and Rahmstorf 2002).

Instabilities in the Earth system could be explored by subjecting Earth system models to a noise and systematically tuning this noise until a resonance is achieved (defined by a significant amplification of the variability in internal model variables at a characteristic frequency). The resonance would be indicative of multiple equilibrium states, which might yield abrupt changes under anthropogenic forcing, but it would also give insights into the magnitude of the abrupt change and the amount of noise needed to trigger such a state change. Related ideas have already been successfully applied to complex systems (Majda et al. 1999; Fischer et al 2002). In the latter case, the metastable states of a molecular dynamical system were extracted from time series of the stochastically perturbed system. A similar approach has the potential to yield invaluable insights into abrupt transitions in the Earth system.

Complexity in the Chemistry of the Atmosphere

The stability of chemical systems in the atmosphere is of concern following the discovery of the ozone hole. Tropospheric chemistry is as complex as that in the stratosphere and is of high importance for the health and well-being of humans, as well as the for the functioning of the Earth system. The troposphere is an oxidizing medium, removing compounds emitted naturally by the terrestrial and marine biospheres and pollutants emitted by human activities. It also affects climate in many ways, for example, through the destruction of the potent greenhouse gas methane, CH_4 . Without this cleansing ability, a large range of natural and human-made compounds would accumulate in the atmosphere to very high

concentrations. The most important of the oxidizing species in the atmosphere is the highly reactive hydroxyl radical, OH.

Because of its short lifetime, the concentration of OH shows large variations in space and time. Models indicate that the regions with the highest abundance of OH are located over the tropics. Therefore, most of the self-cleansing reactions of the troposphere occur in the tropical zone, and this region consequently plays a key role in the regulation of atmospheric composition. In spite of the well-established importance of the OH radical in atmospheric chemistry, measurements of this species are still very sparse. In particular, there are no measurements at all of OH over the tropical continents, where anthropogenic perturbations of the atmospheric oxidant cycle are likely to occur and where they may have the most pronounced effect. Such measurements are urgently needed as a test of our basic understanding of atmospheric photochemistry.

Ecological Complexity and Earth System Functioning

Major anthropogenic activities have manifested their impacts on the global biosphere. Overfishing and eutrophication due to human activities stand out as among the most serious issues threatening the marine biosphere worldwide. Myers and Worm (2003) recently reported that about 90% of the large predatory fish biomass has been removed from the world's oceans, with removal rates being highest with the onset of post-World War II industrial fisheries. Ecosystem impacts include intermediate results of compensation by nontarget fish populations. However, because of accelerated expansion of fishing in the 1980s, fishing pressure exceeded these compensatory mechanisms and has now led to unequivocal evidence of decline in most pelagic and ground fisheries of continental shelves. There is less evidence for oceanic fishing grounds. Given the importance of top-down controls on the dynamics of marine ecosystems, there is the possibility that such overfishing could lead to significant, abrupt changes to marine ecosystems (often called "regime shifts"), which reverberate through to lower trophic levels such as zooplankton, phytoplankton, and bacteria.

Other anthropogenic pressures on the coastal zone have led to abrupt changes (from an Earth system perspective) in the functioning of marine ecosystems. For example, because of its ubiquity, human-dominated waste loading is altering coastal ecosystems on a global scale. This has led to a state of eutrophication, the latter being a biogeochemical response to heavy nutrient loading. Primary producers synthesize organic matter in addition to what is delivered as waste from populations and manufacturing systems. The excess organic matter undergoes oxygen-consuming degradation. From the 1970s to the 1990s, anthropogenic loads of dissolved inorganic nitrogen increased about sixfold to 13.3 Tg (1 Tg = 10^{12} g). Over the same period, dissolved inorganic nitrogen increased fourfold to 1.6 Tg.

There are secondary consequences of eutrophication. Hypoxic zones under certain conditions can release nitrous oxide to the atmosphere during the process of denitrification. This has been documented for the western shelf of India, which obtains dissolved inorganic nitrogen inputs both from seasonal upwelling and from horizontal delivery from land. In the Gulf of Mexico, hypoxia is a major summer feature, but denitrification has not been detected. Competing microbial pathways such as dissimilatory nitrate reduction to ammonium may keep the reactive substrate in the water column.

The ecosystem effects of eutrophication are just beginning to be studied. Jackson et al. (2001) argue that historical overfishing, including the removal of suspension feeders because of trawling and other top predators, has resulted in the simplification of trophic and other functional relationships and the microbialization of coastal systems. Phase shifts include the shift from long-lived macrophytes to short-lived epiphytes and the increasing frequency of phytoplankton blooms and cyanobacteria. In sediments, shifts toward heterotrophic microbial processes are evident.

It remains to be seen how overfishing and eutrophication will alter biogeochemical cycles and the resulting global inventories of carbon, nitrogen, phosphorus, and silica. There is, seemingly, consensus that the nearshore estuarine systems most proximal to human populations are carbon sources, being net heterotrophic and microbe dominated. In open shelf and oceanic domains, the systems remain as carbon sinks, being net autotrophic. Despite the apparent capacity of oceanic ecosystems to assimilate the impacts of waste loading and overfishing, governments should consider the imminent collapse of coastal ecosystems as symptoms that demand immediate mitigation.

In contrast to their marine equivalents, terrestrial ecosystems generally lost many of their top predators and underwent trophic pathway simplification several centuries ago. There has not been widespread ecosystem failure as a result. Terrestrial ecologists generally favor a more "bottom-up" view of ecosystem regulation.

There is evidence (Tilman 1999; Loreau et al. 2001) of a relationship between terrestrial biodiversity and aspects of ecosystem functioning, particularly when the biodiversity is expressed in "functional type" terms. However, it appears that quite modest levels of biodiversity are sufficient to maintain processes such as primary production and nutrient cycling at close to maximum levels, and there is no obvious threshold below which loss of ecosystem function or services suddenly occurs.

If such an effect does occur, it is most likely within the radically simplified agricultural systems. Widespread failure of these systems would have dire consequences for human welfare, but not for life on Earth. Agricultural systems not only replace more diverse natural and seminatural systems with a small group of domesticates, they also simplify the landscape when conducted at large scale, and within the agricultural species, the genetic base is progressively narrower.

The argument, largely unsupported by data, is that agricultural systems of low spatial and genetic diversity are more vulnerable to pest outbreaks and environmental change.

Pandemics

Critical breakpoints for the Earth system may also lie in the still very inadequately explored interactions of climate and environmental change, socioeconomic development, and human and animal health. The preeminent feature of the Anthropocene is that human activities have become a geophysical and biogeochemical force that rivals the "natural," nonhuman processes. This implies that major discontinuities in the socioeconomic domain may lead to corresponding disruptions in the biogeochemical/physical domain. An example of such a discontinuity may be the spread of a new disease vector resulting in a pandemic. High population densities in close contact with animal reservoirs of infectious disease make the rapid exchange of genetic material possible, and the resulting infectious agents can spread quickly through a worldwide contiguous, highly mobile human population with few barriers to transmission. Warmer and wetter conditions as a result of climate change may also facilitate the spread of diseases. Malnutrition, poverty, and inadequate public health systems in many developing countries provide large immune-compromised populations with few immunological and institutional defences against the infectious disease. An event similar to the 1918 Spanish Flu pandemic, which is thought to have cost 20 to 40 million lives worldwide at the time, may result in over 100 million deaths worldwide within a single year. Such a catastrophic event, which is not considered to be unlikely by the epidemiological community, might lead to rapid economic collapse in a world economy dependent on fast global exchange of goods and services. In a worst case this might lead to a drastic, and probably long-lasting, change in the way humans affect the Earth system.

Current Knowledge Base on Abrupt Changes

The preceding discussion of the "Achilles' heels" of the Earth system can be summarized as follows:

- It is well established that abrupt changes in major features of Earth system functioning can occur and indeed have occurred. Prominent examples include the D/O events and the formation of the Antarctic ozone hole, which have been regional in scale but may trigger impacts at the global scale.
- It is further known where some of these abrupt changes can occur. In addition to the two examples given above, the switching of northern African vegetation between savannah and desert, the existence or not of Greenland ice cover, and the large regions of permafrost in northern Eurasia are further areas of instability where a part of the Earth system can change relatively rapidly from one well-defined state to another.

- Not all of the potential abrupt changes in all components of the Earth system (climate, chemical, biological, human and their coupling) are known, nor are they likely to be. However, promising techniques exist to identify more of them.
- Beyond knowing that a potential abrupt change might occur, it is more difficult to determine what triggers abrupt changes or how close a system may be to a threshold.
- Both the magnitude and rate of human forcing are important in determining whether an abrupt change is triggered in a system or not. In general, the probability of abrupt changes in complex systems increases with the magnitude and rate of forcing.
- The Earth system as a whole in the late Quaternary appears to exist in two states (glacial and interglacial) with well-defined boundary conditions in atmospheric composition (CO_2 , CH_4) and climate (inferred temperature) (Petit et al. 1999). The nature of the controls on the boundary conditions are not known (cf. Watson et al., this volume) nor are the consequences of the present large, ongoing, human-driven excursion beyond these boundaries (e.g., Keeling and Whorf 2000). Model-based exploration of Earth system phase space cannot yet find a third equilibrium state at a warmer, higher CO_2 level than the interglacial (Falkowski et al. 2000).

SYSTEMS OF MODELS AND OBSERVATIONS

What sort of models and data do we need to understand and anticipate Earth system change in the Anthropocene?

The Current State-of-the-Art in Climate Projection

Many critical Earth system characteristics are undergoing rapid change in the Anthropocene, but climate change is the most obvious example of where international research has been organized to address a policy-relevant question. The production of climate change projections for the twenty-first century, as embodied in the assessments of the IPCC, is multidisciplinary (see Figure 16.1). The drivers of climate change (anthropogenic emissions of greenhouse gases and aerosols and land-use change) are derived using socioeconomic models, based on a range of "storylines" regarding population growth, economic development, and technological change. High emissions scenarios assume major technological developments to permit extensive use of nonconventional oil and gas resources. We do not know how plausible such developments might be. The emissions are then used to drive atmospheric chemistry models, which produce corresponding scenarios of changes in the concentrations of greenhouse gases and aerosols for use within climate models. The resulting climate projections are used by impact modelers, who estimate the extent to which the projections will

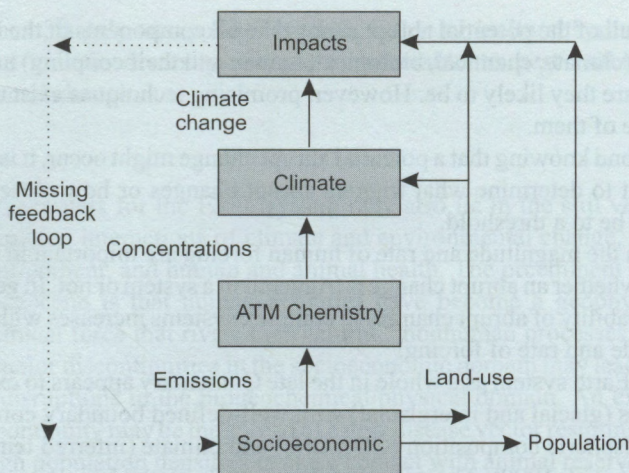


Figure 16.1 Schematic showing the methodology used by the IPCC to produce model projections. Continuous arrows show the inputs and outputs to each model in the chain. Dotted line shows the missing impacts-to-socioeconomic responses loop.

affect humankind (e.g., through climate-driven changes in water and crops, as well as changing demands driven by population growth).

Each stage of this process involves models of some complexity and with widely differing structures. The socioeconomic models operate at large regional scales (e.g., North America, Europe), are not gridded, and are often based on optimization assumptions under equilibrium conditions. By contrast, atmospheric chemistry models and GCMs use a grid (e.g., with boxes of equal size in latitude and longitude) to represent the Earth system and are based on deterministic differential equations. The computational cost of running these models is very high, which limits the resolution they can employ (i.e., the minimum size of the gridboxes) to about 250 km at present. On the other hand, impacts are generally felt at finer scales (e.g., at the scale of a river catchment for hydrology), so it is normally necessary to “downscale” the outputs of the GCM before they can be used to drive impact models, either using statistical techniques or high-resolution regional climate models, which currently operate with gridboxes of about 50 km. The validity of these downscaling models has not yet been well tested.

At each stage of the IPCC modeling process there is a change in the way the Earth system is represented, which leads to difficulties at the interfaces, requiring downscaling, upscaling, or arbitrary definition of the outputs of one model in terms of the inputs to another. In addition, the modeling methodology is “one-way” in the sense that information flows bottom-to-top in Figure 16.1 but not the reverse. This means that the subcomponents of the modeling system do not generally feedback on one another in the way in which the real Earth system operates, which of course is a principal deficiency.

New Tools Required to Guide Policy in the Anthropocene

The methodology outlined in Figure 16.1 has been remarkably successful in coordinating different research disciplines to address a key aspect of Earth system change. However, this approach is not capable of answering some of the most critical questions posed by scientists and policy makers. Here we list these questions and suggest the new tools and methodologies that these demand.

1. *How will the coupled Earth system respond to anthropogenic forcing?*

As noted previously, the existing climate modeling methodology lacks feedbacks between subsystems of the Earth system. Some recent attempts have been made to include feedbacks between the physical, biological, and chemical parts of the Earth system through a two-way coupling of the various subsystems (e.g., Jones et al. 2003; Johnson et al. 2001). Integrated assessment models also represent the feedbacks between the socioeconomic and natural parts of the Earth system, but they do this at the expense of drastic simplifications in the submodels (e.g., climate may be represented solely by global mean temperature). An intermediate complexity approach is required in which the subcomponents are "traceable" to more comprehensive models but which are sufficiently economical to enable exploration of additional feedbacks.

2. *What are the impacts of climate change at the scale of communities?* This question is difficult to answer because climate models are currently too coarse-grained for regional impacts assessments. Furthermore, impacts are generally determined by climatic extremes (e.g., droughts or floods), and these are not well represented at low resolutions. Higher-resolution climate projections are therefore required, either through embedding regional climate models in GCMs or through basic enhancements in GCM resolution as computer power increases. The latter approach is typified by the Japanese Earth Simulator Centre, which has plans to run global climate projections with a resolution of 10 km, compared to 250 km in current GCMs. Note, however, that such significant increases in resolution may compromise the ability to include the full Earth system feedbacks, to explore abrupt change, and to assess the uncertainty in the projections (see the first and third questions in this section).

3. *What are the uncertainties in the projections?* A key deficiency in climate modeling has been an inability to define "error bars" for projections. Some qualitative measure of uncertainty is given by the spread in results from different GCMs; however, policy makers actually require a more meaningful estimate of the "probability distribution function" (PDF) for future climate. The probability of certain critical thresholds being crossed (e.g., > 2K warming by 2050) is required for risk analysis. Attempts are now underway to define the climate PDF using "physics ensembles," which are made up of structurally identical models each of

which has different plausible sets of internal parameters. Climate projections are then weighted by their ability to reproduce key features of the current climate (with "better models" receiving more weight). This approach is promising but requires many climate model runs (~hundreds) rather than a "one shot" model. There is, therefore, a tension between greater model resolution and sufficient model speed to enable such estimation of uncertainty. A fundamental difficulty remains, however, in that the socioeconomic future of the global society cannot be predicted, since this system is indeed chaotic and in principle unpredictable, except for some overarching features and within some limited period of time. Furthermore, the results of projections of future developments cannot be tested against real data, since in reality there will be only one experiment and we are in the midst of it. In addition, there are still considerable differences in the regional changes of climate as simulated by different models.

4. *Can we reduce uncertainty?* The inclusion of additional feedbacks in the Earth system is likely to increase rather than reduce the spread among model projections, since the additional components provide new ways for the models to differ. However, more complete Earth system models will provide a more realistic (and larger) estimate of the uncertainty in the behavior of the real Earth system. The uncertainty is valuable information in its own right (e.g., for assessing the probability of some abrupt change occurring); however, the fact that it appears to be growing is in danger of being misinterpreted by our paymasters (who may wish to wait for less ambiguous results and conclude that since more money into model development increases uncertainty, less money might have the desired effect!).

Model development alone is unlikely to reduce uncertainty in the foreseeable future, and some uncertainties can never be eliminated since the climate system is chaotic. Still, additional data on changes in the Earth system can constrain models and thereby reduce uncertainty. Thus, there is an urgent need to maintain and develop the monitoring of the Earth system (e.g., through the Global Climate Observing System). A wide spectrum of Earth system quantities needs to be monitored, ranging from the maintenance of historical records (e.g., of riverflow) to the utilization of new satellite data (e.g., CO₂ from space). There is also an urgent need for socioeconomic data of particular interest in the context of climate change (e.g., data on land use and land-use change).

Further Developments in Earth System Modeling

In addition to the developments outlined above, full Earth system models must consider other processes. Dynamics of the biological and human systems of the planet are relevant at the global scale and, through their interactions, must be

included in simulations of the dynamics of the whole Earth system. At present, with the focus of many global models on climate change, the primary emphasis in terms of human activities has been on greenhouse gas emissions, land-use change, and aerosol emissions. The influence of biological systems is modeled mainly through their biogeochemical cycles.

There are, however, other important aspects of Earth system dynamics that are not climate related. For example, the growth of the world's population, evolution of technology, transformations of the economy or relevant changes in global lifestyles, and political ambitions occur with or without climate change. Such factors are becoming increasingly global in scale and character. These dynamics in the human part of the Earth system have significant, first-order effects upon the whole system, and future projections of biosphere-sociosphere interactions are undoubtedly crucially important in simulating the future evolution of the Earth system as a whole. Biogeochemically, the material basis of the human economy, which at the core concerns the distribution and redistribution of materials extracted from the physical and biological systems of the world under various constraints, can be treated as an extension of "natural" biogeochemical flows to flows through human systems. As noted in the preceding section, these societal processes are presently included as "given" scenarios external to the model itself and not included in the internal dynamics of the model.

Thus, three types of activities are currently on the near-term agenda to develop more complete Earth system models:

1. Coupling full terrestrial biosphere models (Dynamic Global Vegetation Models, DGVMs) to climate models to capture not just primary feedbacks of the terrestrial biosphere to the climate system but also, in a consistent way, the effects of climate on the terrestrial biosphere (similar models, the so-called "Green Ocean" models, are being developed for putting the marine biosphere into Earth system models).
2. Expansion of DGVMs to incorporate fully human land use, particularly agriculture and water use, including the development of parameters that allow quantification of ecosystem services to society.
3. Coupling of DGVMs through their land-use modules to economic models (including endogenous technology dynamics), themselves perhaps drawing upon models of lifestyle dynamics.

The technical challenges of such model development and coupling are considerable. For example, climate and biosphere models are time-step models, whereas economic models are mostly based on optimization approaches under equilibrium conditions. Economic models are therefore not gridded but rather act upon 10 to 20 world regions, whereas climate and biosphere models are spatially explicit (similar differences occur in the data sets available for parameterizing and driving the models). Coupling requires considerable efforts in downscaling and development of software metastructures for fuzzy information exchange

(hard-wired coupling may be less preferable than a “mutual envelope” approach). With respect to the economic system, models of price dynamics have to be interpreted more consciously in terms of material and energy flows, including those that are not currently assigned monetary value (such as use of clean air). In the social sphere, formulating quantified scenarios of lifestyle dynamics seems an urgent task. Progress is being made in all of these fields, but many efforts are still at an early stage. The promise of enhanced understanding is great. For example, such integrated socioeconomic–biophysical models may be used to explore whether gradual changes in the biophysical realm of the Earth system can trigger abrupt changes in the socioeconomic sphere.

Observations designed to monitor the anthroposphere in the context of the Earth system involve the human subsystem as well. Various human dimension and related initiatives have yet to concur on a shortlist of high priority areas that require monitoring, in part because of the large variation in the ways in which different communities perceive the problems inherent in the anthroposphere. Focusing on the immediate or proximate factors that register humanity’s demands on the Earth system and resources (e.g., Turner 2002), such a list would include: population variables (e.g., fertility, age structure, rural–urban mix), wealth and changes of behavior associated with changes in wealth (e.g., diet), energy–material consumption and waste emissions by level of economic development location, efficacy of institutional controls on resource–environment issues, and critical land-use/land-cover trajectories. Visionary approaches to building an Earth-observing system focused on socioeconomics are embodied in such projects as the Geoscope (www.sustainability-geoscope.net).

Models of Biodiversity

The biological complexity of the planet also plays a role in the functioning of the Earth system. The capability to predict where, and to what degree, biodiversity is likely to be lost as a result of the combined impact of climate change, land-use change, direct use, and the impact of pollutants is an emerging field. In the climate change field, models have progressed from simple bioclimatic envelope approaches that are applied to whole biomes, to similar models applied to functional types and then individual species (including nonclimatic constraints), to fully dynamic models that track the movement of populations to determine if they can keep up with the rate of change. The next step will be “ecosystem” models, which take into consideration the presence of competitors, mutualisms, food and predator species, as well as habitat structure.

On another track, integrated assessment models aim at expressing the complexity of biodiversity in synthetic index terms (macro-ecological indicator), and then relate changes in this index to various types and intensities of human activities. This allows scenarios to be developed, targets set, and performance to be monitored. Examples include the RIVM natural capital index (ten Brink 2000) and the SafMA biodiversity intactness index (in preparation).

TECHNOLOGICAL FIX AND SUBSTITUTION

How effective will technological substitution be in dealing with increasing impacts of the human–environment relationship on the Earth system?

The preceding sections make a strong case for the necessity of a societal response to global change. A business-as-usual approach to the future will not achieve global sustainability. Prominent among the proposed responses to global change are technological options, ranging from treatment of the fundamental causes of the problem, such as the development of noncarbon-based energy systems, to treatment of the symptoms of the problem through highly controversial geo-engineering approaches.

Throughout history, society has responded in two principal ways to environmental vagaries, flux, hazards, and drawdown, including resource depletion: *move*, either through designed mobility as in pastoral nomadic systems or “forced” relocation owing to environmental or resource degradation as exemplified in the salinization-relocation pattern of irrigation in Mesopotamia (Adams 1965); and *change techno-managerial strategies*, as in the adoption of fossil-fuel energy or genomics (Grübler 1998). The first option has decreased in significance in an evermore crowded and politically controlled world. The second option — to modify or transform biophysical conditions in order to gain a measure of “control” over some portion of the environment or to deliver a substitute for a depleted resource — is not only ancient but has become a defining element of our species (Diamond 1997; Redman 1999; Turner et al. 1990). Such responses are labeled technological fix and substitution. Modern society has raised the bar in pursuit of techno-managerial solutions, with long-standing success in regard to deliveries of food, fuel, and fiber to increasingly larger and highly consumptive populations (Grübler 1998; Kasperson et al. 1995; Kinzig et al., this volume).

This approach to human–environment relations and ensuing problems is the cornerstone of the modern conditions of life, be it the Industrial Revolution or the Green Revolution. Society has become so reliant on ever-increasing advances in technology to overcome the next generation of problems that a disconnect or gap has emerged between the environmental consequences of production and consumption and the public consumer (e.g., Sack 1992). Technological solutions also offer a means to avoid the thorny issues involved in alternative solutions that are often perceived to affect lifestyles.

Science for sustainable development confronts technological fix and substitution in the face of natural and anthropogenic changes in the Earth system, culminating in global environment change. Technology constitutes one of a set of responses to deal with the problems inherent in changes in the Earth system. Indeed, some researchers believe that technological solutions will, in fact, liberate the Earth system of many of its current threats (Ausubel 2000, 2002). As noted above, however, these changes have no known analogues (Steffen et al. 2004),

and some of them constitute qualitative shifts in the structure and functioning of the Earth system. These qualities raise a fundamental question and set of sub-questions about the efficacy of technological fix and substitution *alone* to cope with the problems: What evidence exists to indicate that the changes underway in the Earth system constitute a no-analogue situation, not only in the changes themselves but also in the sole use of technological fix and substitution to address these changes?

Furthermore, regarding technological fix and substitution, does the evidence suggest:

- Reduced effectiveness to address changes at the scale of the Earth system?
- Excessive cost to develop and deploy them compared to alternatives (e.g., societal changes or preservation of goods and services of the Earth system)?
- Temporal mismatch between the capacity of the potential fixes to become operative and the increasing environmental problems, with potential abrupt changes?

The antecedents and antiquity of global environmental change notwithstanding, the human–environment condition has entered a new phase that constitutes a qualitative or threshold shift: (a) The capacity of humankind to change directly the biogeochemical cycles that sustain the structure and functioning of ecosystems and the biosphere as a whole. Anthropogenic input into many of these cycles now exceeds nature's input (Steffen et al. 2004; Turner et al. 1990). For example, more nitrogen is now fixed from the atmosphere as a result of human activities than all natural nitrogen-fixing processes in the terrestrial biosphere combined. Technology also introduces new, synthetic compounds into the Earth system. The release of the well-known chlorofluorocarbons (CFCs) is only one of many examples; globally over 100,000 industrial chemicals — many of them unknown in the natural world — are in use today (Raskin et al. 1996). (b) The combination of these emissions has complex, systemic consequences, that is, numerous unforeseen feedbacks with far-ranging consequences and connections invariably leading to "surprises." Perhaps the most dramatic example to date was the formation of the ozone hole over Antarctica.

This qualitative shift in the human impacts on the Earth system generates at least three new conditions to confront technological responses:

1. Earth system changes are global in scale; climate and other environmental changes are taking place worldwide. Whereas these changes vary by region and locale, the historical societal response of moving the location of production and consumption to account for these changes or those of resource depletion or degradation appears to be attenuated. An increasingly occupied and crowded planet reduces new spaces in which to move and fosters more intensive uses of the spaces already occupied.

2. Systemic changes are inherently transboundary, and thus changes in one place affect places far away. For example, the burning of fossil fuels in North America and western Europe probably made a major contribution to drought and subsequent famine and starvation in the Sahel region in the 1970s and 1980s (Rotstajn and Lohmann 2002).
3. Many of the changes currently underway drive processes that operate over long timescales with impacts that will affect the functioning of the Earth system long after the forcing function is relaxed. Examples include the atmospheric emissions of CO₂, whose effects have a lifetime of 50–150 years; the closure of the ozone hole, which despite the reduction in CFC emissions following the Montreal Protocol, is expected to take at least four or five decades, perhaps more, to close fully; and the accumulation of reactive nitrogen compounds in terrestrial and marine ecosystems with consequences that will be played out over century timescales.

To date, humankind has directed technology to environmental problems focused primarily on resource extraction of food, fuel, and fiber, on the reduction in resource stocks (enlarging or changing), or on reducing the consequences of environmental hazards (e.g., drought to floods). The Earth system and the major societal activities affecting it have redirected these characteristics. The impacts of waste from production and consumption, such as CO₂ emissions, are equivalent to or exceed the consequences of resource extraction, including land-cover conversion, and the changes underway have shifted from resource stocks to functioning of ecosystems and the biosphere. It is highly improbable that ecosystems can be significantly altered and their many functions replaced technologically. It is even less probable that technological replacements can be found for the functioning the Earth system as a whole, especially its ability to absorb and process wastes.

The kind of environmental changes underway challenge the historical relationships between technology and environment. Other factors, however, affect this relationship as well.

The temporal dimension of the development and deployment of new technologies varies considerably by case, and the overall process may be accelerating through time (Grübler 1998). The Green Revolution, for example, transpired rapidly; it took no more than thirty years from the founding of research development centers for hybrid crops to dominate the world (Conway and Ruttan 1999). Regardless, changes currently underway in the Earth system are likely to play out over much longer timescales unless technologies of “reversal” are developed (see examples quoted above). In addition, the Earth system could shift in ways that would change the very aims or goals of technological controls. For example, if an abrupt shutdown of the THC in the North Atlantic Ocean leads to no net warming or even cooling, societies in northern Europe would have to abandon plans to change their infrastructure to cope with strong warming.

These characteristics of the Earth system and changes underway indicate that there are few analogues regarding past technological fixes and substitutions. Also, the lock-in of significant growth in human population (Population Reference Bureau 2002) and the near-universal call for increases in per capita consumption within the developing world indicate a world in 2050 that will demand more, not less, from the Earth system (Kates *et al.* 2001). These conditions require new ways of approaching human–environment problems that deviate from “business as usual” and are capable of provisioning (resources) and conserving (ecosystem–biosphere) more while degrading and changing less (Earth system). The “precautionary principle,” uncertainty and surprise, and the no-analogue conditions noted above suggest caution in a solution focused solely on technological fix and substitution and raise consideration of alternatives that address values, institutions, and other societal structures (Kinzig *et al.*, this volume).

These nontechnical solutions need not be necessarily invented anew; various examples exist or are emerging, research on which provides clues for exploration. For example, comparative case study work indicates that sociopolitical structures which facilitate the flow of information among many stakeholders and decision makers tend to encourage learning in such forms as recognition of local and regional threats to environmental systems, a critical step toward any action taken (Kasperson *et al.* 1995; Social Learning Group 2001). Likewise, structures providing checks and balances on resources and environmental decisions tend to prevent potential threats to extant uses of local and regional ecosystems that might otherwise be inflicted from decisions made from afar. For example, absence of these checks and balances permitted the Soviet government to reduce the Aral Sea ecosystem to near-death conditions, despite local recognition of its demise (Micklin 1988; Kasperson *et al.* 1995). This observation, however, does not mean that structures promoting strong checks and balances necessarily lead to improved environmental conditions. Finally, it is important to recognize that global structures designed to provide some measures of checks and balances regarding environmental issues constitute a relatively new phenomenon (Young 1999, 2002).

These structures are emerging within a political–economic process labeled globalization in which production, consumption, and information operate in worldwide networks that connect virtually every place. This process is argued by some to attenuate the repercussions of environmental and resource disasters, for example, by marshaling large amounts of food aid to famine areas (Kates and Parris 2003). Alternatively, others claim that it amplifies environmental problems by disconnecting more than ever in human history, the location and impacts of production and consumption, which exacerbates environmental degradation in marginalized locations. The large-scale destruction of the Indonesian forests for the international timber industry (Brookfield *et al.* 1995; Dauvergne 1997) is a case in point. Less explored is the concept that increasing globalization

potentially sets the stage for worldwide collapses of social and environmental systems because the geographical, and in some cases temporal, buffering of sub-systems is diminished. In terms of technological substitution, globalization could, in principle, increase the ability of new technologies to diffuse and penetrate more rapidly from their point of development to other regions of the world.

The challenges to technological fix and substitution notwithstanding, technology will constitute part of the solutions directed to environmental problems — global and local — in the future. Indeed, inasmuch as technology is responsible for some of these problems, so can it help to alleviate them. Technological advances promise increasing efficiencies in existing technologies whereas various emerging technologies will likely be critical in the future; these include genomics and biotechnology, nanotechnology and information, as well as “alternative” energy.

RESEARCH CHALLENGES

Significant progress has been made over recent years in understanding the dynamics of the Earth system in the Anthropocene. The complexities of atmospheric composition in influencing the climate system are increasingly well understood; the possibility of abrupt changes in the Earth system is apparent and promising approaches for understanding and anticipating them are being developed; and a suite of Earth system models of varying emphases and complexities is being developed to simulate past, present, and future functioning of the planet. Such progress helps to sharpen the focus of the near-term research effort and leads to a set of research questions to help guide Earth system science over the next five to ten years.

Climate Sensitivity

- What is the quantitative importance of greenhouse gas–aerosol–cloud dynamics in enhancing or counteracting the direct radiative effects of greenhouse gases in the atmosphere?
- What are the radiative and chemical characteristics of aerosol particles, their emission/formation processes, regional and intercontinental dispersion, and deposition on a regional and global basis?
- Can the energy balance at the Earth’s surface be closed at the regional and global scales for the Anthropocene? If so, what insight does that give about the climate sensitivity to greenhouse gases?

Earth System Geography

- What strategies are required to achieve a better balance of research and observation effort around the world?

Abrupt Changes

- What is the catalogue of possible abrupt changes in the Earth system resulting from a model-based, systematic exploration of Earth system phase space using equilibrium and stochastic resonance approaches?
- What research approaches can be developed to anticipate abrupt changes in the socioeconomic sphere of complex, coupled human–environment systems?

Models and Observations

- What spectrum of Earth system models is required to examine the wide range of questions associated with Earth system functioning, from exploring critical thresholds and abrupt change to high resolution impacts studies? How can we build a “traceable” spectrum of Earth system models?
- What is the best strategy for developing models that incorporate the human dimension as a fully interactive component of the Earth system?
- How can data-model fusion be developed further to provide a more complete diagnosis of the Earth system? What critical parameters need to be observed routinely to monitor the “vital signs” of Earth system functioning?
- What is the best strategy to test and improve Earth system models in the context of gradually evolving global change punctuated by extreme events in nature and society?

Technological Substitution

- What is the probability that technological change will be able to support the projected global population of 2050 at significantly higher average levels of consumption while reducing the emissions of CO₂, CH₄, and other gases and particles to the atmosphere and slowing down and ultimately stopping the degradation of marine and terrestrial ecosystems?
- Will technological fix and substitution directed to environmental concerns be offset by that directed to other concerns (e.g., economic growth)?
- Which institutional and organizational structures have proven most effective (including public acceptance) in enforcing environmental regulations under different human–environment conditions and different scales of governance (Kinzig et al., this volume)?
- What kinds of programs and policies effectively support the conversion to and maintenance of consumption-production processes (industrial and agricultural) that are more environmentally benign (compared to extant or conventional processes) in both developed and developing countries?

ACKNOWLEDGMENTS

We thank Bob Scholes for his written contributions to this report.

REFERENCES

- Adams, R.M. 1965. Land Behind Baghdad: A History of Settlement on the Diyala Plain. Chicago: Univ. of Chicago Press.
- Anderson, T.L., R.J. Charlson, S.E. Schwartz et al. 2003. Climate forcing by aerosols — A hazy picture. *Science* **300**:1103–1104.
- Ausubel, J. 2000. The great reversal: Nature's chance to restore land and sea. *Technol. Soc.* **22**:289–301.
- Ausubel, J. 2002. Maglevs and the vision of St. Hubert, or the great restoration of nature: Why and how. In: Challenges of a Changing Earth: Proc. of the Global Change Open Science Conf., Amsterdam, 10–13 July 2001, ed. W. Steffen, J. Jäger, D. Carson, and C. Bradshaw, pp. 175–182. Berlin: Springer.
- Barnett, T.P., D.W. Pierce, and R. Schnur. 2001. Detection of anthropogenic climate change in the world's oceans. *Science* **292**:270–274.
- Brookfield, H.C., L. Potter, and Y. Byron. 1995. In Place of the Forest: Environmental and Socioeconomic Transformation in Borneo and the Eastern Malay Peninsula. Tokyo: United Nations Univ. Press.
- Clark, P.U., S.J. Marshall, G.K.C. Clarke et al. 2001. Freshwater forcing of abrupt climate change during the last glaciation. *Science* **293**:283–287.
- Claussen, M., C. Kubatzki, V. Brovkin et al. 1999. Simulation of an abrupt change in Saharan vegetation at the end of the mid-Holocene. *Geophys. Res. Lett.* **24**:2037–2040.
- Conway, G., and V.W. Ruttan. 1999. The Doubly Green Revolution: Food for All in the Twenty-First Century. Ithaca, NY: Comstock Publ.
- Crutzen, P. 1995. My life with O₃, NO_x, and other YZO_xs. In: Les Prix Nobel (The Nobel Prizes), pp. 123–157. Stockholm: Almqvist and Wiksell Intl.
- Crutzen, P.J., and E. Stoermer. 2001. The "Anthropocene." *Glob. Change Newsl.* **41**: 12–13.
- Dauvergne, P. 1997. Shadows in the Forest: Japan and the Politics of Timber in Southeast Asia. Cambridge, MA: MIT Press.
- DeMenocal, P.B., J. Ortiz, T. Guilderson et al. 2000. Abrupt onset and termination of the African Humid Period: Rapid climate response to gradual insolation forcing. *Quat. Sci. Rev.* **19**:347–361.
- Diamond, J. 1997. Guns, Germs, and Steel: The Fates of Human Societies. New York: Norton.
- Dijkstra, H.A. 2000. Nonlinear Physical Oceanography. Atmospheric and Oceanographic Library Series. Dordrecht: Kluwer Academic.
- Falkowski, P., R.J. Scholes, E. Boyle et al. 2000 The global carbon cycle: A test of our knowledge of Earth as a system. *Science* **290**:291–296.
- Feudel, U., and W. Jansen. 1992. CANDYS/QA—a software system for the qualitative analysis of nonlinear dynamical systems. *Intl. J. Bifurc. & Chaos* **2**:773–794.
- Fischer, A., C. Schutte, P. Deuflhard, and F. Cordes. 2002. Hierarchical uncoupling—coupling of metastable conformations. In: Computational Methods for Macromolecules: Challenges and Applications, Proc. 3rd Intl. Workshop on Algorithms for Macromolecular Modeling, ed. T. Schlick and H.H. Gan, Lecture Notes in Computational Science and Engineering Series, vol. 24, pp. 235–259. Berlin: Springer.

- Gammaitoni, L., P. Honggi, P. Jung, and F. Marchesoni. 1998. Stochastic resonance. *Rev. Mod. Physics* **70**:223–287.
- Ganopolski, A., and S. Rahmstorf. 2001. Rapid changes of glacial climate simulated in a coupled climate model. *Nature* **409**:153–158.
- Ganopolski, A., and S. Rahmstorf. 2002. Abrupt glacial climate changes due to stochastic resonance. *Phys. Rev. Lett.* **88**:038501-1–038501-4.
- Gardiner, C.W. 1994. *Handbook of Stochastic Methods*, 2nd ed. Berlin: Springer.
- Grootes, P.M., M. Stuiver, J.W.C. White, S. Johnsen, and J. Jouzel. 1993. Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. *Nature* **366**:552–554.
- Grübler, A. 1998. *Technology and Global Change*. Cambridge: Cambridge Univ. Press.
- IPCC (Intergovernmental Panel on Climate Change). 2001. *Climate Change 2001: The Scientific Basis*. Working Group I Contribution, Third Assessment Report of the IPCC, ed. J.T. Houghton, Y. Ding, D.J. Griggs et al. Cambridge: Cambridge Univ. Press.
- Jackson, J.B.C., M.X. Kirby, W.H. Berger et al. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293**:629–637.
- Johnson, C.E., D.S. Stevenson, W.J. Collins, and R.G. Derwent. 2001. The role of climate feedback on methane and ozone studied with a coupled ocean-atmosphere-chemistry model. *Geophys. Res. Lett.* **28**:1723–1726.
- Jones, C.D., P.M. Cox, R.L.H. Essery et al. 2003. Strong carbon cycle feedbacks in a model with interactive CO₂ and sulphate aerosols. *Geophys. Res. Lett.* **30**:1479–1482.
- Kasperson, J.X., R.E. Kasperson, and B.L. Turner II, eds. 1995. *Regions at Risk: Comparisons of Threatened Environments*. Tokyo: United Nations Univ. Press.
- Kates, R.W., W.C. Clark, R. Corell et al. 2001. Sustainability science. *Science* **292**:641–642.
- Kates, R.W., and T.M. Parris. 2003. Long-term trends and a sustainability transition. *Proc. Natl. Acad. Sci. USA* **100**:8062–8067.
- Keeling, C.D., and T.P. Whorf. 2000. Atmospheric CO₂ records from sites in the SIO air sampling network. In: *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge Natl. Laboratory. Oak Ridge, TN: U.S. Dept. of Energy.
- Kleinen, T., H. Held, and G. Petschel-Held. 2003. The potential role of spectral properties in detecting thresholds in the Earth system: Application to the thermohaline circulation. *Ocean Dyn.* **53**:53–63.
- Levitus, S., J.I. Antonov, T.P. Boyer, and C. Stephens. 2000. Warming of the world ocean. *Science* **287**:2225–2229.
- Loreau, M., S. Naeem, P. Inchausti et al. 2001. Biodiversity and ecosystem functioning: Current knowledge and future challenges. *Science* **294**:804–808.
- Loutre, M.F., and A. Berger. 2000. Future climatic changes: Are we entering an exceptionally long interglacial? *Clim. Change* **46**:61–90.
- Majda, A.J., I. Timofeyev, and E. Vanden Eijnden. 1999. Models for stochastic climate prediction. *Proc. Natl. Acad. Sci. USA* **96**:14,687–14,691.
- Mann, M.E., R.S. Bradley, and M.K. Hughes. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophys. Res. Lett.* **26**:759–762.
- Micklin, P. 1988. Desiccation of the Aral Sea: A water management disaster in the Soviet Union. *Science* **241**:1170–1176.

- Myers, R.A., and B. Worm. 2003. Rapid worldwide depletion of predatory fish communities. *Nature* **423**:280–283.
- Nobre, C.A., P. Artaxo, M.A.F. Silva Dias et al. 2002. The Amazon Basin and land-cover change: A future in the balance? In: Challenges of a Changing Earth, Proc. of the Global Change Open Science Conf., Amsterdam, NL, 10–13 July 2001, ed. W. Steffen, J. Jäger, D. Carson, and C. Bradshaw, pp. 137–141. Berlin: Springer.
- NRC (National Research Council). 2002. Abrupt Climate Change: Inevitable Surprises. Washington, D.C.: Natl. Academy Press.
- Petit, J.R., J. Jouzel, D. Raynaud et al. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**:429–436.
- Pikovsky, A.S., and J. Kurths. 1997. Coherence resonance in a noise-driven excitable system. *Phys. Rev. Lett.* **78**:775–778.
- Population Reference Bureau. 2002. 2002 World Population Data Sheet. http://www.prb.org/pdf/WorldPopulationDS02_Eng.pdf
- Rahmstorf, S. 2000. The thermohaline circulation: A system with dangerous thresholds? *Clim. Change* **46**:247–256.
- Ramanathan, V. 1981. The role of ocean–atmosphere interactions in the CO₂ climate problem. *J. Atmos. Sci.* **38**:918–930.
- Raskin, P., M. Chadwick, T. Jackson, and G. Leach. 1996. The sustainability transition: Beyond conventional development. Polestar Series 1. Stockholm: Stockholm Environment Institute.
- Redman, C.L. 1999. Human Impact on Ancient Environments. Tucson: Univ. of Arizona Press.
- Rotstayn, L.D., and U. Lohmann. 2002. Tropical rainfall trends and the indirect aerosol effect. *J. Climate* **15**:2103–2116.
- Sack, R.D. 1992. Place, Modernity, and the Consumer's World. Baltimore: Johns Hopkins Press.
- Schneider, S., B.L. Turner II, and H. Morehouse Garriga. 1998. Imaginable surprise in global change science. *J. Risk Res.* **1**:165–185.
- Shah, M. 2002. Food in the 21st century: Global climate of disparities. In: Challenges of a Changing Earth, Proc. of the Global Change Open Science Conf., Amsterdam, 10–13 July 2001, ed. W. Steffen, J. Jäger, D. Carson, and C. Bradshaw, pp. 31–38. Berlin: Springer.
- Social Learning Group. 2001. Learning to Manage Global Environmental Risks, 2 vols. Cambridge, MA: MIT Press.
- Steffen, W., A. Sanderson, P.D. Tyson et al. 2004. Global Change and the Earth System: A Planet Under Pressure. The IGBP Book Series. Berlin: Springer.
- ten Brink, B.J.E. 2000. Biodiversity indicators for the OECD Environmental Outlook and Strategy: A feasibility study. Report 402001014. Bilthoven: RIVM.
- Tilman, D. 1999. The ecological consequences of changes in biodiversity: A search for general principles. Robert H. MacArthur Award Lecture. *Ecology* **80**:1455–1474.
- Turner, B.L., II. 2002. Toward integrated land-change science: Advances in 1.5 decades of sustained international research on land-use and land-cover change. In: Challenges of a Changing Earth, Proc. of the Global Change Open Science Conf., Amsterdam, 10–13 July 2001, ed. W. Steffen, J. Jäger, D. Carson, and C. Bradshaw, pp. 21–26. Berlin: Springer.
- Turner, B.L., II, W.C. Clark, R.W. Kates et al. 1990. The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years. Cambridge: Cambridge Univ. Press.

- UN (United Nations). 2001. World Population Monitoring 2001. Population, Environment and Development. ST/ESA/SER.A/203. New York: UN Publ.
- Young, O.R. 1999. Governance in World Affairs. Ithaca: Cornell Univ. Press.
- Young, O.R. 2002. Can new institutions solve atmospheric problems? Confronting acid rain, ozone depletion and climate change. In: Challenges of a Changing Earth, Proc. of the Global Change Open Science Conf., Amsterdam, 10–13 July 2001, ed. W. Steffen, J. Jäger, D. Carson, and C. Bradshaw, pp. 87–91. Berlin: Springer.